METALLURGICALLY BASED DEVELOPMENT OF DUAL-PHASE THIN HOT STRIPS BY ARVEDI I.S.P. TECHNOLOGY

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ABSTRACT

Steels with a lean chemical compositions were designed by metallurgical modelling, laboratory tests and industrial trials in order to achieve on thin hot rolled strips dual-phase (DP) grades, acting on the peculiar thermo-mechanical process by Arvedi I.S.P. technology.
Steel chemical composition was tuned in order to decrease the flow-stress of austenite and maintain enough hardenability. The formation of fine MA constituent was promoted through proper austenite conditioning and adequate carbon enrichment of austenite during controlled cooling on the run out table. Suitable set-up of laminar cooling sections was established describing simultaneously the strip temperature evolution and austenite phase transformation by a mathematical model.
Optimum process conditions to produce as-rolled DP 600 grade were identified for 3.0 mm to 1.5 mm thick coils.
A steel tailored to produce 1.2 mm thick hot strips, able to develop grade DP600 after intercritical treatment during the hot dip galvanizing line, was also developed. The steel chemical composition and the continuous heating during hot dip galvanizing were adjusted to stabilize the austenite formed in the infracritical region, avoiding cementite formation during fast cooling and short holding in the zinc bath.

KEYWORDS

Dual-phase steel, hot coils, mathematical modelling, microstructure, strength, formability, I.S.P. technology.

INTRODUCTION

The attention towards high strength dual-phase (DP) steels increased significantly in the last years. Especially the automotive industry has shown a great interest in DP steels due to the possibility to reduce weight of vehicles and to increase the passenger safety at a very competitive cost.

A DP steel is characterised by a microstructure consisting of a dispersion of high C martensite and retained austenite (MA constituent) in a polygonal ferrite matrix (usually 75% to 90% in volume). This microstructure gives good combinations of strength and ductility, continuous yielding, and high work hardening rate (YS/UTS = 0.55-0.65). In particular, the typical values of yield strength (YS) and ultimate tensile strength (UTS) for a DP600 grade are 300 MPa to 480 MPa and 570 MPa to 670 MPa, respectively, with a minimum total elongation (El) of 22% [1].

A DP microstructure can be obtained in a hot coil either directly, controlling both hot rolling process and cooling on the run out table (ROT), or in a continuous annealing line by an intercritical heat treatment, followed by a proper cooling, which promotes the required amount of fine well dispersed MA islands in polygonal ferrite.

The production of thin as-rolled strips with thickness (Th) from 1.2 mm to 1.8 mm, characterised by a DP microstructure, is one of the current technological challenges.

In this paper the metallurgical design of 1.2 mm to 3.0 mm hot rolled strips of grade DP600, which have a lean chemical composition, exploiting the peculiar thermo-mechanical process of Arvedi I.S.P. technology at Cremona steelworks [2], is presented. Metallurgical modelling, laboratory tests and industrial trials have been used to identify steels able to produce DP microstructures with the desired mechanical properties either directly from the hot strip mill ($t \geq 1.5$ mm) or after an intercritical heat treatment performed during hot dip galvanizing ($t < 1.5$ mm).

1. METALLURGICAL CONCEPTS FOR DP STEELS

The chemical composition of an as-rolled DP steel is usually designed to develop given austenite phase transformation characteristics when the steel is properly processed on the strip-mill. The continuous cooling transformation (CCT) diagram of the steel shall exhibit an elongated ferrite C-curve, in order to form the required amount of polygonal ferrite for a wide range of cooling rates, a suppressed or delayed pearlite nose to avoid pearlite formation during cooling and coiling, and a gap between ferrite and bainite regions to reduce the need of a very strict control of ROT cooling.

In order to obtain the above characteristics, low carbon contents and adequate combinations of Mn, Cr and Mo are usually required [3]. However, acting on the thermo-mechanical process and ROT controlled cooling, it can be possible to develop DP microstructures even eliminating Mo and reducing Mn and Cr contents. A lean composition decreases the values of the mean flow stress of austenite and can allow hot rolling of very thin strips, still maintaining suitable hardenability.

In particular, a proper austenite conditioning is necessary to promote the formation of fine polygonal ferrite (80% to 90% in volume) during ROT cooling and produce as-rolled DP600 strips. The finish hot rolling temperature shall be in the range Ar_3 to $Ar_3 + 40$ °C, in order to have a work-hardened and fine austenite (size < 15 µm) which enhances ferrite development. Also ROT cooling pattern must be properly designed. The cooling strategy aims at promoting ferrite formation and carbon enrichment (C > 0.4%) of austenite not yet transformed by means of a three stages cooling: a rapid water laminar cooling just after finish rolling (1^{st} step) is interrupted at a proper temperature where ferrite formation kinetics is very fast (i.e. close to the ferrite nose temperature) for few seconds (2^{nd} step), followed by a second fast cooling (3^{rd} step) down to coiling temperature (CT). Values of CT lower than martensite start temperature (Ms) allow the full transformation of remaining austenite into MA even when its hardenability is low.

An alternative route to produce DP grades, usually applied to cold rolled thin strips, is based on an intercritical heat treatment by a continuous annealing line. In this case, chemical composition and heat treatment conditions are designed to develop both an adequate amount of austenite in the infracritical region and an enrichment in C, Mn and other elements able to stabilise austenite and avoid cementite formation together with MA constituent during subsequent cooling.

2. AS-ROLLED DP600 STRIPS

Starting from previous CSM expertise [3] and literature review [4-7], a preliminary chemical composition range has been selected for the development of DP600 coils by I.S.P. process.

HOME

The C content and alloying additions have been adjusted in order to have enough hardenability to form DP structures, but without achieving high values of austenite mean flow stress (MFS), in order to manufacture thin as-rolled strips of grade DP600.

Using empirical relationships [8], the effect of main chemical elements on austenite MFS has been calculated for a 2 mm thick strip (Table 1).

Table 1 Calculated variation of MFS for a 2 mm thick strip (ΔMFS) as a function of the content of C, Mn, Mo and Cr.

	ΔMFS (MPa/mass%)
C	125
Mn	23
Mo	17
Cr	21

The control of C, Mn, Mo and Cr contents within given limits results important to avoid excessive rolling forces during hot rolling of thin strips.

Low carbon ($0.05\% \le C \le 0.1\%$) Mo-free steels with various combinations of Mn ($0.9\% \le Mn \le 1.7\%$) and Cr ($0.03\% \le Cr \le 0.35\%$) have been selected as lean low-cost steel versions to develop thin strips of grade DP600 by I.S.P. process (Th $\le$ 3 mm).

Experimental tests

The main transformation characteristics of the selected steels have been studied by a set of laboratory tests.
After austenitisation (900 °C for 600 s), the following dilatometric tests have been carried out:

1. Determination of isothermal (TTT) and CCT diagrams of the chosen steels.
2. Deformation of samples at 800-850 °C before cooling, in order to assess the effect of austenite deformation in promoting ferrite formation.
3. Simulation of three stages cooling on the ROT, in order to identify the best process conditions (temperature of cooling interruption, holding time, cooling rates of 1st and 3rd stage, etc.).

All samples have been characterised in terms of microstructure and hardness.

Metallurgical modelling

A metallurgical phase transformation model developed by CSM [9] has been used to define the optimum process conditions on the ROT for the selected steels. The model, made of a thermal module coupled with a phase transformation module, is able to describe the thermal evolution during cooling, taking into account the heat generated by phase transformation, and to predict the volume fraction of the microstructural constituents at the end of the cooling. Furthermore, to better reproduce the metallurgical phenomena involved in the phase transformation of low-C steels, the carbon enrichment of austenite during the transformation is considered, shifting the transformation curves of bainite and decreasing the Ms temperature as a function of present C content into austenite [10].

The model, which has an user-friendly interface, has been specialised for the I.S.P. layout at Cremona steelworks. Each water cooling bank is divided into different sub-sections for realistic simulation of the actual cooling regimes: a zone with high heat transfer coefficient, under the direct impingement of the water curtain, between two adjacent zones with a low heat transfer coefficient, the so called “parallel flow” zones [11, 12]. A pair of switches is associated to each water cooling section, one for the upper laminar cooling, the other for lower water sprays. The switches enable or disable the relevant cooling device according to the desired cooling strategy.

The thermal module has been tuned defining the heat transfer coefficient values for both the upper laminar cooling and lower water sprays. Thermal profiles recorded during industrial production of strips with different thicknesses and speeds, and various sets of cooling banks, have been used for fine tuning. The phase transformation module, based on the knowledge of the TTT diagram of the steel, has been calibrated using dilatometric data.

The whole model has been validated comparing the calculated and experimental coiling temperatures for strips with Th = 1 – 4 mm, processed with different ROT cooling patterns (Fig.1).

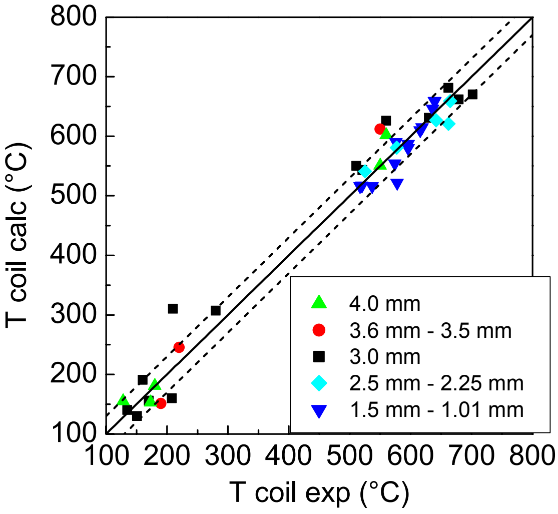


Fig.1 Comparison between experimental and calculated CT. Dotted lines define the range of ± one standard deviation (± 30 °C).

Model application

After model validation, a set of simulations has been carried out to identify the most promising chemical composition and process conditions to manufacture thin as-rolled DP600 strips.
Different layouts of the cooling banks on the ROT have been simulated. An example of the calculated thermal profiles and volume fractions of microstructural constituents is reported in Fig. 2 for steels A and B, where steel B is more hardenable than steel A. Steel A has been subjected to three cycles (coded 1 to 3), differing mainly for CT. It has been shown that decreasing CT the volume fraction of MA increases. The most promising cycle for steel A is cycle 3, which allows to develop about 14% MA. The same cycle 3 simulated for steel B produces about 25% of MA. Introducing an interruption of the rapid cooling (cycle 4) a greater amount of ferrite is formed and MA is reduced to 8%.

HOME

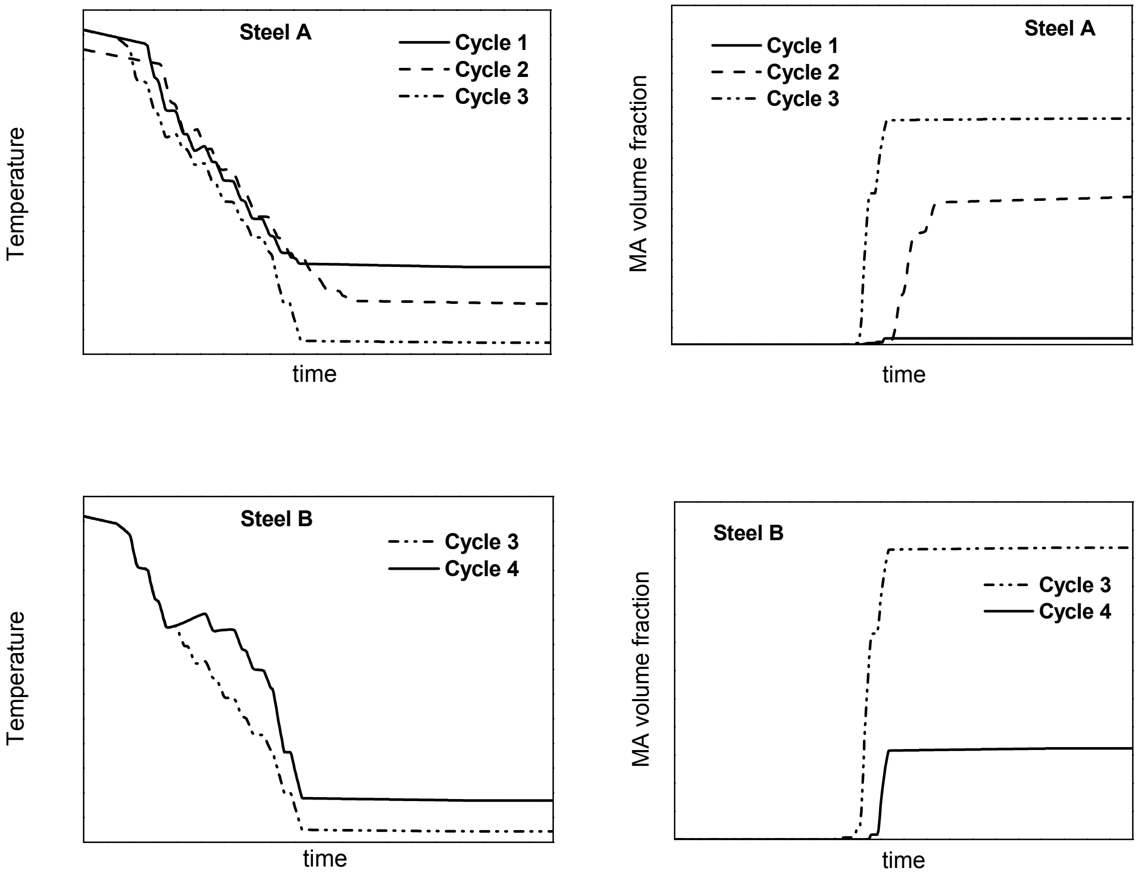


Fig.2 Examples of calculated thermal profiles and MA volume fractions for steels A and B, where steel B is more hardenable than steel A.

On the basis of these calculations, pilot trials have been successfully performed and the feasibility of DP600 thin strips by I.S.P. process has been completed through preliminary industrial trials at Cremona steelworks.

The hot rolling schedule has been set up following the indications of a CSM metallurgical model which describes austenite work-hardening and softening during hot deformation processes [13].

To define the layout of the water cooling banks to be used for the industrial production, a set of simulations has been carried out with the thermal-metallurgical model. Thermal profiles and phase transformations have been predicted for strips with different thickness. The three stages cooling for a 3.0 mm strip has been tuned using selected combinations of open and closed cooling banks identified by mathematical modelling. The calculated strip thermal cycles along the ROT for three layouts of laminar cooling banks are shown in Fig.3 a). Cycles C and D are characterised by a slightly different set of cooling banks in the 2nd stage, where alternant open and closed cooling banks have been used. In the case of reference Cycle E, all cooling banks have been opened.

A good agreement is seen between the calculated profiles and the intermediate and coiling temperatures measured during the industrial trials (Fig.3).

Cycle C, which allows to achieve both a longer holding time in the 2nd stage at about 680 °C and a low CT, is able to develop the target volume fraction of enriched austenite which transforms into MA at the end of coiling, as confirmed by the microstructural analysis.

HOME

A similar cooling strategy on the ROT has been adopted for 2.0 mm and 1.8 mm thick strips, using during the 2nd stage a proper combination of open and closed cooling banks to interrupt the accelerated cooling and promote ferrite formation. The calculated thermal profiles are compared with the experimental temperatures in Fig.3 b). Also in this case both calculated and experimental microstructures confirmed the possibility to obtain a DP grade. An example of calculated volume fractions of ferrite and martensite for a 2.0 mm thick strip is reported in Fig.4 a). The actual microstructure of the same strip (Fig.4 b) shows a ferrite matrix with about 12% of dispersed MA islands, confirming the good predictions of the model.

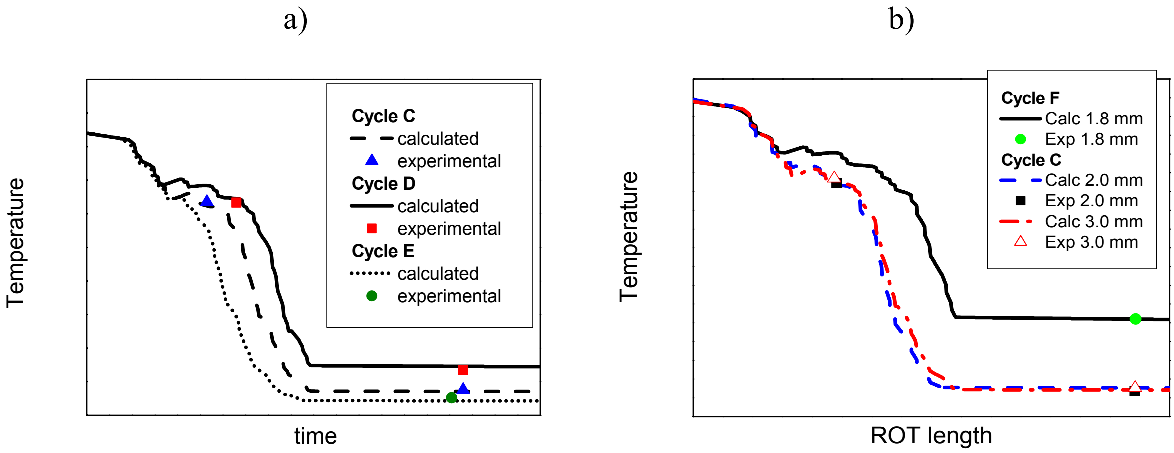
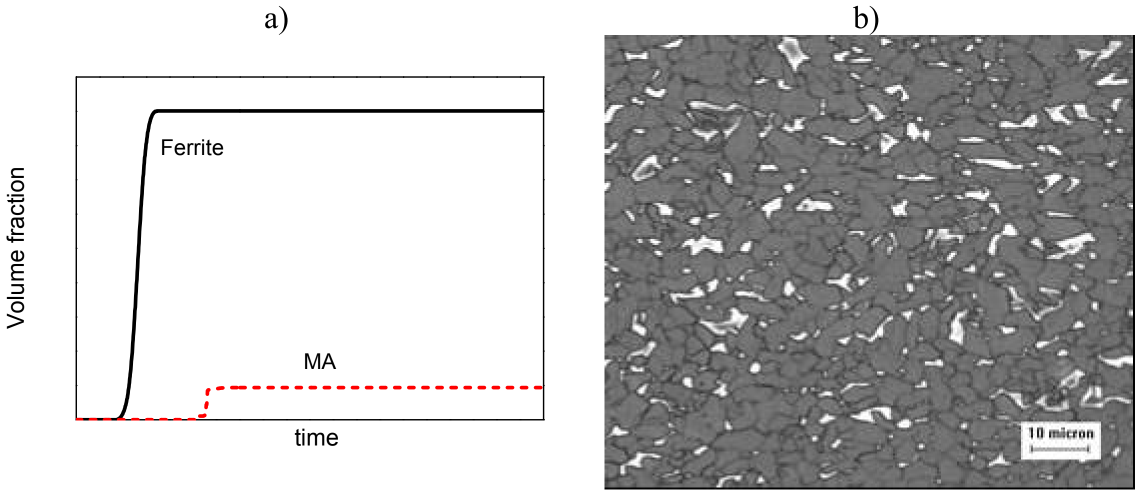


Fig. 3 Calculated thermal profiles and temperatures measured during industrial trials:
a) different ROT layouts for a 3.0 mm thick strip;
b) strips with different thickness and ROT layouts.



MA ~ 12%

Fig. 4 a) Calculated volume fraction of ferrite and MA constituent for a 2.0 mm thick strip cooled on the ROT using cycle C;
b) Microstructure of 2.0 mm thick strip produced using cycle C on the ROT.

Industrial production

The industrial production has been made by the Arvedi plant in Cremona, based on the I.S.P. technology.

HOME

The I.S.P. technology is one of the most innovative ones for the steel production involving a thin slab caster, an in-line 3-stand High Reduction Mill, an inductive heater, an intermediate coiling station (Cremona Furnace) and a finishing mill of 5 stands with a down-coiler, for a total length of 170 m (Fig. 5). The plant based on ISP technology can allow very high productivity rates (more than 1.000.000 tons of steel with only one continuous casting line) and significant energy savings, and it can manufacture ultrathin hot rolled strips in a wide range of steel grades such as low, medium and high carbon, HSLA, boron grades, weathering, alloyed and Dual Phase steels. In particular the Dual Phase steels can take advantage from the thin slab casting and from the in-line rolling technologies because of the better control of the process parameters due to the rolling at constant speed and constant temperature.

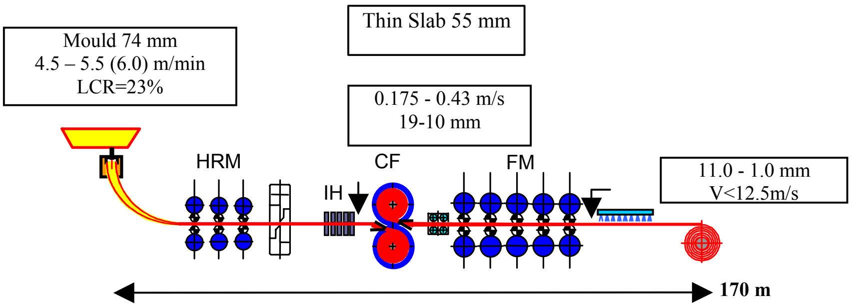


Fig. 5 Layout of I.S.P. line.

Heats of the selected lean chemical composition have been processed by I.S.P. at Cremona steelworks to produce 1250 mm wide strips of grade DP600, with different thickness (3.0 mm, 2.0 mm, and 1.8 mm)

The water banks have been set in order to have on the ROT a cooling pattern which follows the strategy defined during the feasibility study.

The coils have been characterised in terms of microstructure (Fig. 6) and longitudinal tensile properties (Table 2).

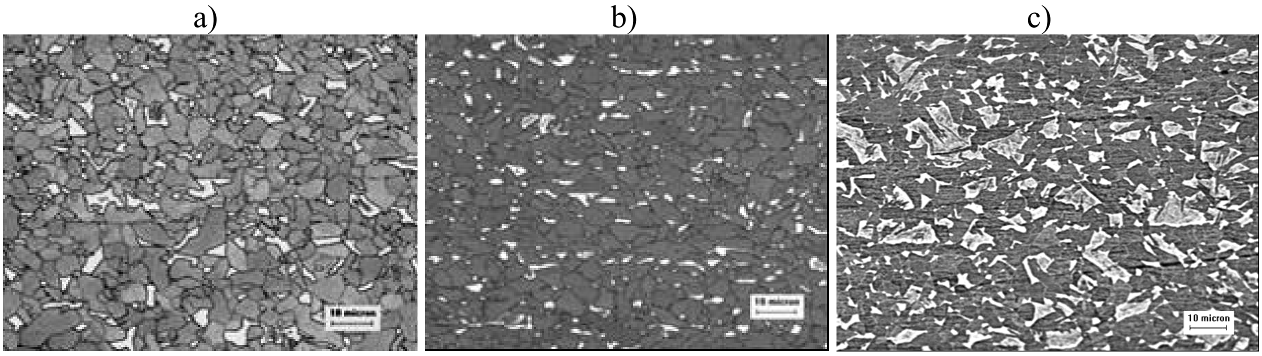


Fig. 6 Microstructure of the DP600 strips analysed at the optical microscope: a) 3 mm thick; b) 2 mm thick; c) 1.8 mm thick.

HOME

Table 2 Longitudinal tensile properties and microstructure constituents of the coils produced by I.S.P. process.

Strip Thickness (mm)	YS (MPa)	UTS (MPa)	YS/ UTS	El (%)	Ferrite (%)	MA (%)	Bainite (%)	Pearlite (%)	FGS*** (µm)
3.0	356	615	0.58	33	85	15	0	0	5
2.0	353	630	0.56	25	86	14	0	0	4
1.8*	404	640	0.63	22	83	17**		0	4

*after skinpass; **MA + Bainite; *** FGS = Ferrite Grain Size.

All strips have shown continuous yielding. A DP microstructure, characterised by a uniform dispersion of MA islands in a fine polygonal ferrite matrix, has been usually developed (Fig. 6). In the case of 1.8 mm thick strips also a significant amount of bainite was detected (Fig. 6 c) and Table 2), but the desired grade has been achieved.

The consistency of microstructure and tensile properties has been checked for selected coils which have been sampled along their length. Maximum variability of YS and UTS is less than 10%. This result is related to the high capability of I.S.P. process, equipped with intermediate induction heater and Cremona furnace, to control in a very narrow range both finish rolling temperature and rolling speed.

In the case of 1.5 mm thick strips (YS = 464 MPa, UTS = 691MPa, El = 21%), tensile strength is close to the upper limits of the requirements. The reason has been found in a large amount of second phase (MA + bainite > 20%). Therefore, cooling pattern on the ROT needs further tuning, taking into account the higher strip speed. This result confirms the indications from the model that the production of very thin as-rolled DP strips is quite difficult because the holding time during slow cooling (2nd stage) is not long enough to form adequate amount of polygonal ferrite. An alternative route for very thin as-rolled DP strips has been investigated and results are reported in section 3.

Properties of grade DP600 by I.S.P.

The bake-hardening (BH) behaviour of 2.0 mm and 3.0 mm thick strips has been assessed after 2% pre-deformation and a subsequent ageing at 170 °C for 1200 s. The BH values (Table 3) are comparable with those reported in literature for steels of similar compositions (60 MPa-100 MPa) and with those calculated using the following empirical relationship [14]:

$$\mathrm{BH}\ [\mathrm{MPa}] = 77 + 11.24*[(T\ (^{\circ}\mathrm{C}) - 200)/30] + 3.71*[(t(\mathrm{s})/60 - 8)/6] \qquad (1)$$

Table III Measured (exp.) and calculated (calc.) BH values.

Strip Thickness (mm)	BH exp. (MPa)	BH calc. (MPa)
2.0	75	73
3.0	74	

Also formability of the coils has been characterised. The Forming Limit Diagrams (FLD) obtained for 2.0 and 3.0 mm thick strips are reported in Fig. 7.

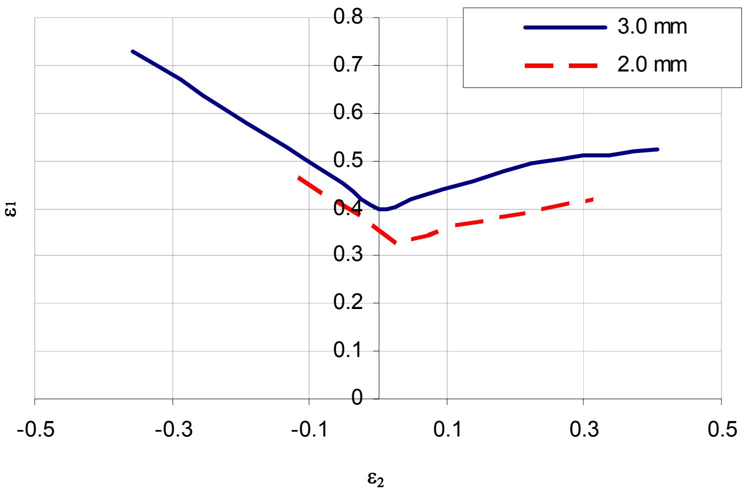


Fig. 7 Forming limit diagrams for the 2.0 mm and 3.0 mm thick strip.

The 3.0 mm thick strips have been employed for the production of discs for wheels (Fig. 8) which successfully passed the fatigue tests.

Fig. 8 Disc for wheel made with 3.0 mm thick DP600 strip produced by I.S.P. process.

3. INTERCRITICALLY DP THIN HOT STRIPS

In the case of thickness smaller than 1.5 mm, since the coil production directly from the hot strip mill needs a very narrow window for ROT cooling conditions, in order to develop hot rolled strips of grade DP600 an intercritical heat treatment in a continuous hot dip galvanizing line has been investigated.

Both laboratory tests and mathematical modelling have been applied to identify proper chemical composition and thermal cycles to produce very thin hot coils of grade DP600.

The mathematical simulations have been performed by means of two models: the first one, based on ThermoCalc [15], calculates the austenite formed at the equilibrium during the infracritical heating and its carbon enrichment; the second one, based on an empirical approach [9], predicts the decomposition of austenite during the subsequent cooling and short holding in the Zn bath.

The thermal cycle must promote the formation of an adequate amount of austenite during the intercritical heating and allow its transformation into MA during cooling, avoiding carbide formation.

Starting from the chemical composition used for the production of as-rolled DP steel strips, a set of simulations has been performed to define the optimum thermal cycle parameters to be adopted during hot dip galvanizing. Taking into account the information from literature [16-18], the following parameters were considered: infracritical temperature T_1, holding time t_1 at temperature T_1, cooling rate CR_1 down to zinc bath and holding time t_2 at zinc bath temperature T_2. At the same time a sensitivity analysis on the effect of the main chemical elements has been carried out. Examples of simulations are reported in Fig. 9 and Fig. 10.

The choice of the infracritical temperature is very delicate for the formation of the DP microstructure. Increasing temperature T_1, the volume fraction of austenite increases, but austenite enrichment in carbon is not adequate to promote fully MA formation (Fig. 9 a)). Also cooling rate down to the zinc bath is a very critical parameter (Fig. 9 b)).
From the simulations, it resulted that a DP microstructure with about 15% MA can be obtained with an infracritical temperature of 740 °C - 750 °C and a cooling rate greater than 20 °C/s.

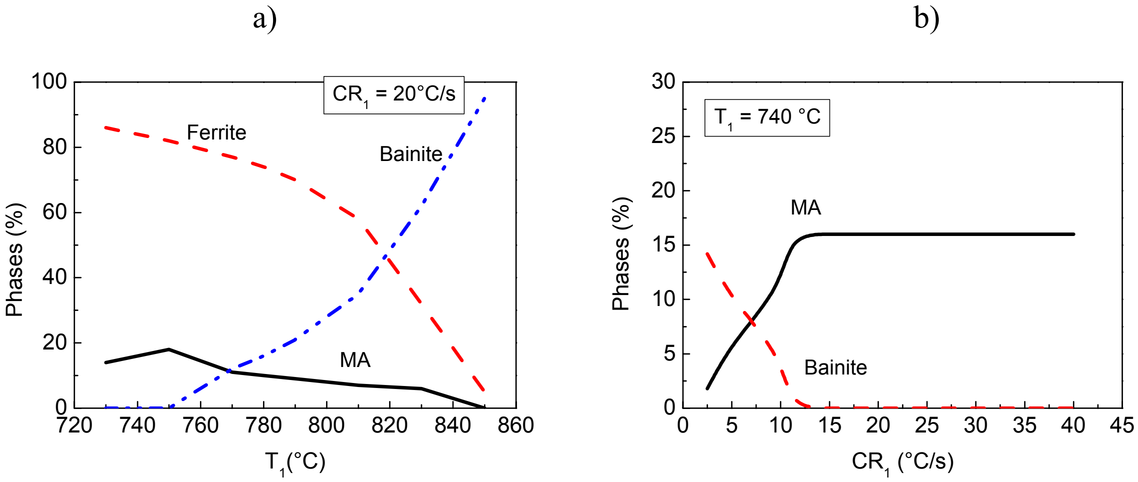


Fig. 9 Volume fraction of microstructural constituents as a function of : a) infracritical temperature T_1; b) cooling rate (CR_1) down to zinc bath.

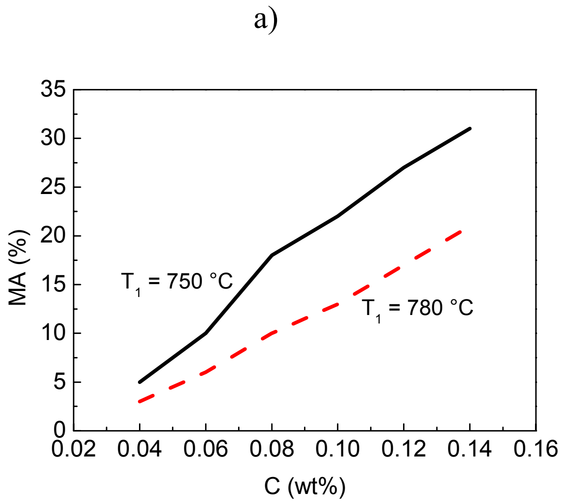


Fig. 10 Volume fraction of MA as a function of: a) Carbon content; b) Manganese content.

Also a set of dilatometric tests has been performed to confirm these calculations and identify the optimum values for holding time t_1, cooling rate CR_1 and holding time t_2.

Three steels have been selected: steel A with low Mn, Cr and Mo contents, steel B with low Mn, high Cr and Mo contents and steel C with high Mn, Cr and Mo contents, but able to develop reasonable rolling forces during the production of 1.2 mm thick as-rolled coils.

The microstructure of the heat treated dilatometric samples has been examined both at the end of each cycle and at intermediate stages by quenching.

Laboratory tests showed that the volume fraction of carbides increases when the cooling rate CR_1 is decreased and when the holding time t_2 is too long. The formation of carbides occurs during cooling from T_1 to T_2 and during holding at T_2. In order to avoid/reduce carbide formation the richest chemical composition (steel C) has been selected.

The effect of zinc bath temperature T_2 has also been studied. Samples taken from steel C have been subjected to the following thermal cycles:

C1, corresponding to the best previously identified process parameters;
C2, which differs from C1 only for a lower zinc bath temperature.

Microstructures characterised by 90%-95% ferrite and 5%-10% MA have been observed in samples after thermal cycles C1 and C2, showing that with the selected chemical composition and with the imposed thermal cycles a DP microstructure can be obtained. However, also traces of carbides have been detected after cycle C1, whereas a lower zinc bath temperature (cycle C2) helps to avoid them.

To verify the mechanical properties that can be obtained with the identified cycles, a 1.2 mm thick hot strip with the selected chemical composition has been produced by I.S.P. at Cremona steelworks and sampled specimens have been subjected to thermal cycles C1 and C2 using a Gleeble machine.

The heat treated samples, examined by optical microscopy, showed a microstructure (Fig. 11) constituted of 96%-92% ferrite and 4%-8% MA, confirming the results obtained with the dilatometric tests.

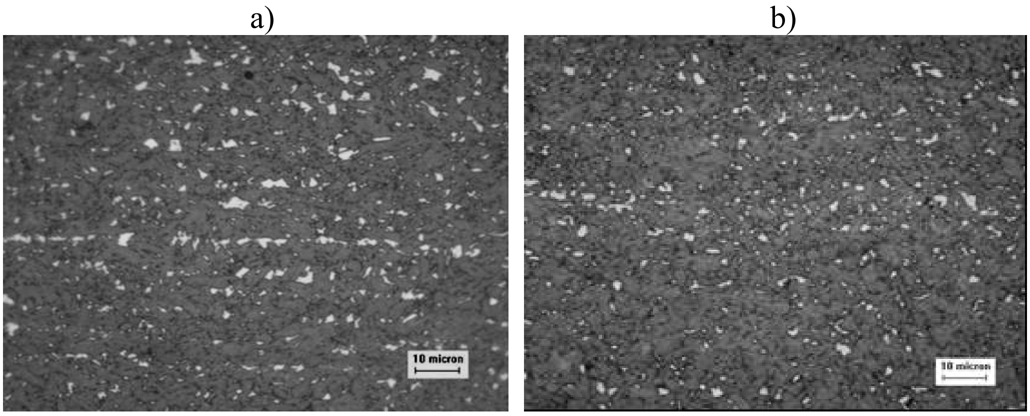


Fig. 11 Microstructures of samples subjected to thermal cycles: a) cycle C1; b) cycle C2.

Table 4 Mechanical properties and volume fraction of MA of the heat treated samples.

Cycle	YS (MPa)	UTS (MPa)	El (%)	YS/ UTS	MA (%)
C1	408	661	18	0.62	5-8
C2	456	692	17	0.66	4-6

Also achieved tensile properties (Table 4) indicate that grade DP600 can be produced by an infracritical heat treatment in the hot dip galvanizing line using the selected chemical composition and a proper thermal cycle.

In the recent revamping of the industrial hot dip galvanizing line at Cremona steelworks, plant changes have been introduced in order to apply to pickled as-rolled thin coils the identified promising process conditions. Industrial trials have been planned.

3. CONCLUSIONS

Steels with a lean chemical compositions were designed by metallurgical modelling, laboratory tests and industrial trials in order to manufacture thin hot rolled strips of grade DP600, acting on the peculiar thermo-mechanical process by Arvedi I.S.P. technology.
The formation of fine MA constituent was promoted through proper austenite conditioning and adequate carbon enrichment of austenite during controlled cooling on the run out table.

DP600 strips with thickness from 3.0 mm to 1.8 mm were produced by Arvedi I.S.P. technology process. BH and FLD assessment showed a good behaviour. The 3.0 mm thick strips were successfully used for the production of discs for wheels which passed the fatigue tests. Also 1.5 mm thick strips were manufactured, but tensile strength values were close to the upper limits of the requirements.

An alternative route for very thin as-rolled DP strips was investigated. A steel for the production of 1.2 mm thick as-rolled strips of grade DP600 by infracritical heat treatment during hot dip galvanizing was developed. A proper thermal cycle was identified to form the desired DP structure, reducing the risk of cementite formation by fast cooling and short holding in the zinc bath. Suitable tensile properties were achieved on specimens taken from a 1.2 mm thick strip produced by I.S.P.

HOME

and laboratory treated to reproduce an optimised infracritical treatment. The industrial hot dip galvanizing line at Cremona steelworks was recently revamped and changes were introduced to apply to pickled thin as-rolled coils the promising infracritical treatment.

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HOME